

Study of a TE (thermoelectric) generator incorporated in a multifunction wood stove

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ABSTRACT

Replacing traditional open fire stoves, characterized by low efficiency, with improved ones is an important challenge for developing countries. Adding TE (thermoelectric) generators can provide electricity that permits not only the use of an electric fan increasing the ratio air to fuel to achieve a complete combustion in the stoves but also the satisfaction of basic needs: light, phones and other electronic devices. A review of existing TE generators for stoves is presented. To test the TE modules, an experimental device has been carried out in our laboratory where a gas heater simulates the stove. The generator set-up is described including the switching electric regulator that stabilizes the fluctuating voltage from the modules and stores the energy in a battery. The performance of the generator mostly depends on the heat transfer through the modules and especially on the thermal contact resistances. First experiments show the influence of the pressure on these resistances. Then a study of temperatures and electrical power measurements is compared to a theoretical analysis using TE and heat transfer equations. The very reasonable value of the obtained contact resistances shows that the mechanical design of the generator is almost optimized. The TE generator has produced up to 9.5 W.

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1. Introduction

Open fires or rudimentary stoves are widely used in developing countries by about 2.5 billion people [1]. These traditional stoves or fires are characterized by low efficiency that results in inefficient use of scarce fuel-wood supplies [2]. These rudimentary fire stoves also lead to high emissions of health damaging air pollutants and smoke is highly linked to ARI (acute respiratory infection) [3,4]. Building clean and efficient cook stoves reduces carbon dioxide and methane emissions while providing social and health co benefits through reduced fuel consumption and reduced indoor air pollution. Improved cook stoves also have the potential to reduce significantly black carbon emissions (short-lived non-CO₂ climate warmer) [5].

Again 1.6 billion people lack access to electricity [6]; providing 10 W to cover basic needs such as light and radio to these low-income populations living mostly in rural areas, will require more than 16 GW power plants (resistive losses in the conductor grid) and all the dispatching. Individual TE (thermoelectric) generators coupled with cook stoves are an interesting option to provide electricity.

The general advantages of a TE generator in this case are:

- It does not need extra energy from the stove.
- The TE generator is incorporated into the cook stove and requires no electrical link with the outside world, unlike solar panels.
- It is silent in operation as it involves no moving parts.
- The maintenance is very light: nothing moves, everything is inside the house, only the battery needs to be changed when it is done for.
- The TE generator works when the stove is on, day and night in good or in rainy weather (monsoon period) unlike solar panels. The battery does not need to be oversized as each use of the stove recharges the battery unlike a solar system where it is necessary to store energy for cloudy days.

As this generator is destined to low-income houses in developing countries, the cost is also an important issue. Previous studies [7–9] have shown that the price per watt is about the same as for solar systems.

The Non Governmental Organization “Planète Bois” develops energy-efficient multifunction mud stoves based on traditional stove designs (Fig. 1). The wood is put into the stove vertically

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Nomenclature

E_o	open circuit voltage of TE module, V	R_{pn}	electrical resistance of one thermocouple, Ω
e_a, e_b, e_c, e_s	distances, m	S_n, S_p	cross-sectional areas of the n -type and p -type pellets, m^2
$h_{contact}$	contact heat transfer coefficient, $W m^{-2} K^{-1}$	T_a	average temperature, $^{\circ}C$
I	current through TE module, A	T_c	cold-side temperature of TE module, $^{\circ}C$
I_{bat}	current through battery, A	T_h	hot-side temperature of TE module, $^{\circ}C$
I_{out}	output current of electronic convertor, A	T_{hi}	temperatures (measurements), $^{\circ}C$
I_L	current in the load, A	T_{sh}, T_{sc}	temperatures of the hot and cold sides of ceramic wafers of the module, $^{\circ}C$
K_{pn}	thermal conductance of one thermocouple, $W K^{-1}$	V_{out}	output voltage of electronic convertor, V
L_n, L_p	leg lengths of the n -type and p -type pellets, m	V_{bat}	battery voltage, V
n	number of thermocouple in a module	V_{TE}	output voltage of TE module, V
P_{av}	electrical power for end users, W	Greek symbols	
P_{elec}	electrical output power, W	α_p, α_n	Seebeck coefficients of the n -type and p -type semiconductors, $V K^{-1}$
p_{elec}^{max}	maximum output power (matched load), W	α_{pn}	Seebeck coefficient of one thermocouple, $V K^{-1}$
Pr	pressure on the TE module, kPa	λ_n, λ_p	thermal conductivities, $W m^{-1} K^{-1}$
q_c	heat released from the cold side, W	$\lambda_{al}, \lambda_{ceram}, \lambda_{solder}$	thermal conductivities of respectively the aluminum, ceramic wafers and metal solders, $W m^{-1} K^{-1}$
q_h	heat absorbed on the hot side, W	ρ_n, ρ_p	resistivities of the n -type and p -type semiconductors, Ωm
q_{sc}, q_{sh}	heat flux through ceramic wafers, W	Abbreviation	
R	thermal resistance, $K W^{-1}$	TE	thermoelectric
R_B	current sense resistance, Ω		
R_{cc}, R_{ch}	contact thermal resistances between wafers and aluminum blocks, $K W^{-1}$		
R_{ce1}, R_{ce2}	thermal resistances of the ceramic wafers, $K W^{-1}$		
R_E	resistance seen by the TE module, Ω		
R_{int}	internal resistance of TE generator, Ω		
R_L	load resistance, Ω		

through the top of the pyrolysis chamber before the lid is closed. The bottom part of the wood rests on a bed of embers maintained through the entry of primary air at this level. Combustible gases are emitted as a result of decomposition by heat (pyrolysis) in the absence of flames and sucked toward a nozzle. These gases are then in contact with the oxygen from the secondary air. The flame then breaks out downstream of the injection of secondary air. The wood burns down so that the bed of embers is renewed. These improved stoves use a smoke extract fan that allows a control of the ratio air to fuel and therefore optimizes the combustion. The fan also permits the use of a horizontal pipe avoiding the necessity of long metal pipes and of building chimneys in countries where local workers do not have the technology to make it go through the roof.

These stoves are called “CLIP” for “Combustion Latérale Inversée Performante” the French terms for “powerful reverse side combustion”. These types of equipment are under validation in Morocco (Fig. 2) where electricity is available. The next important challenge is the providing of countries without electricity with this stove.

The goal of our work is to study the feasibility of using TE modules in this stove in order to generate electricity. The expected power is about 10 W not only for the fan but also for basic needs: lighting, radio and charging cell phones as well as other small electronic devices.

To test the TE modules, an experimental device has been carried out in our laboratory where a gas heater simulates the stove.

The first part of this paper presents a review of existing TE generators for stoves. Then the entire generator set-up is described including the thermal and mechanical parts as well as the switching electric regulator which converts the fluctuating voltage from the TE modules into a constant voltage and stores electrical energy in a battery. After showing the influence of the pressure on the contact resistance, experimental electrical power measurements are compared with the results of a theoretical analysis using TE and heat transfer equations.

2. Review of existing TE generators for stoves

2.1. TE generators

TE generators directly convert a very small part of the heat going through them into electricity as described in Fig. 3. They are composed of three parts: two heat exchangers and a TE module.

The efficiency of the TE module depends on the properties of the materials used for the thermocouples. For the moment semiconductors offer the best efficiency.

The only couple of materials available on the market at a reasonable price is bismuth telluride (Bi_2Te_3). These materials can work at a temperature as high as $260^{\circ}C$ continuously and intermittently up to $380^{\circ}C$. Other materials are being studied for higher temperatures, such as clathrates, skutterudites, alloys Heusler, phases of Chevrel and oxides [10] but are not commercially available.

2.2. TE generators for stoves

In the literature review, only the experimental studies have been selected. The heat generator is the hot smoke of the stove and all the TE modules are made of bismuth telluride (Bi_2Te_3).

Nuwayhid et al. [11] have studied the possibility of using a proportion of the heat from 20 to 50 kW wood stoves, to provide a continuous 10–100 W electric power supply. In a first prototype they used cheap Peltier modules for their TE Generator. The maximum power for a module was very low (1 W) mostly because of the limited temperature difference due to the maximum temperature supported by the module and also because of the geometry which is optimized for cooling and not for generating power. In a following prototype [12] their TE generator used 1, 2 or 3 commercially available low-cost power generator modules. The cold side of the TE modules was naturally cooled with the surrounding

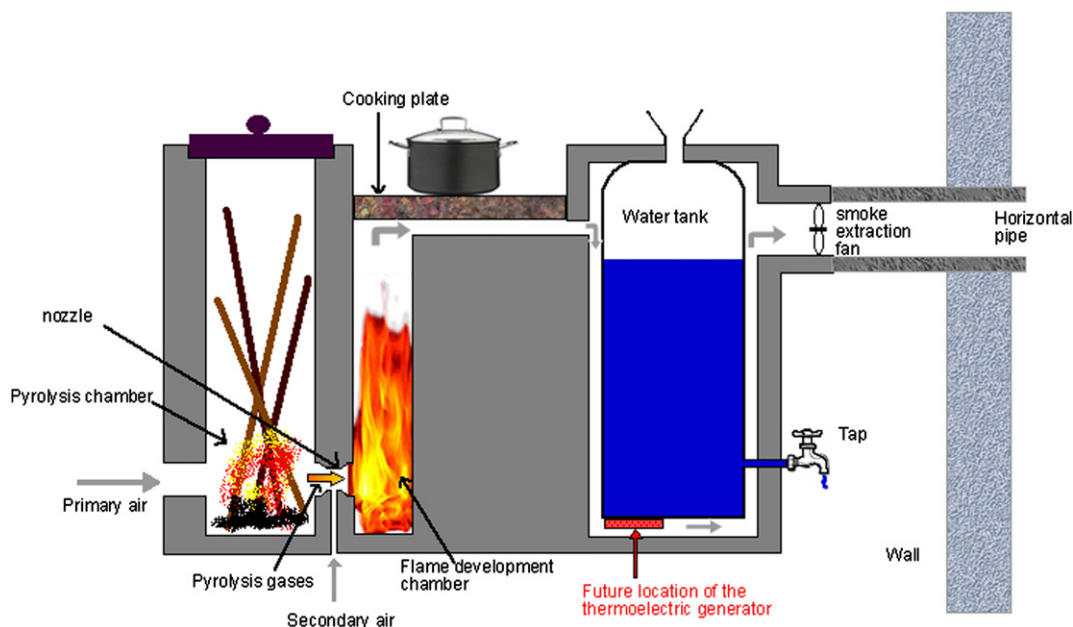


Fig. 1. Schematic of the energy-efficient multifunction mud stove.

air. They got a maximum power of 4.2 W for one TE module and they showed that the output power per module decreased when the number of TE modules in the TE generator increased. This is a result of the reduction of the temperature difference between the hot and cold surfaces. They also made a TE generator using heat pipes for the

heat sink [13]. The maximum power was about 3.4 W. Lertsatitthanakorn [14] investigated the same type of prototype and he got a power output of 2.4 W. He added an economic analysis indicating that the payback period tends to be very short.

Mastbergen and Wilson [7] presented at the ETHOS 2005 congress (Engineers in Technical and Humanitarian Opportunities of Service) a prototype of TE generator with a forced air-cooling for the cold side with a 1 W fan. The net power of 4 W generated by the TE generator was sufficient to power an array of high intensity LEDs (light-emitting diodes). Field tests [15] have been made in different countries but results are not available in the literature.

BioLite [16], an industrial lightweight backpacking stove, has been presented at the 2009 ETHOS conference. The TE generator is only used to create clean, efficient cooking with a forced-air draft fan for this wood burning stove.

“Planète Bois” and our laboratories explore water cooling cold heat sink TE generators [8–17]. “Planète Bois” multifunction cook stoves produce hot water. The best location to put the TE generator is under the water tank as the heat flux from the hot gas to the tank (about 30 L) can be used to produce electricity without losing heat. So there is almost no additional energy cost. The heat exchanges



Fig. 2. “CLIP” stove in Morocco.

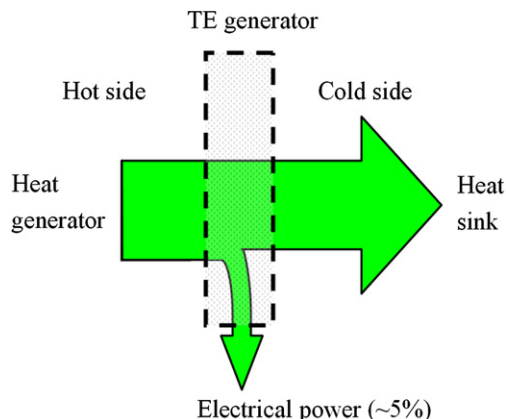


Fig. 3. Basic principle of a TE power generator.

with water are generally better than exchanges with air and the use of water guarantees that the cold heat sink temperature will always stay under 100 °C.

Recently Rinalde et al. [9] presented a forced water cooling system. Their laboratory prototype uses an electric heater for the heat source. They obtained a maximum power of 10 W but needed a pump which certainly decreases the available output power.

The different prototypes are summarized in Table 1.

These results show that it is possible to obtain an electrical power of about 10 W. However, further experiments are necessary to study the feasibility of using thermoelectrical modules with our stove and to improve the generated electrical power.

3. Generator set-up

As the water tank is a fixed part of the stove the TE generator must be installed during the building of the stove. So before installing the generator in a real stove, different experimental TE power generators were made and tested in our laboratory [17,18] using smaller tanks. The obtained results were used to design a new experimental device including an electronic convertor. This new experimental set-up, called TEGBioS II, allows the study of the global performances of the TE generator in real operating conditions. It allows us to test the influence of the thermal contact and the electric part on the output power.

The set-up also permits the experimental study of both the thermal and the electric parts in order to validate a one dimensional steady-state modeling.

After an economic study between modules from Hi-Z Technology (13 W for 103€) and Thermoamic (14 W for 67€), it was chosen for our prototype the Thermoamic model TEP1-12656-0.6 with 126 couples and a size of 56 mm × 56 mm. These modules can work at the temperature of as high as 320 °C continuously and stand with up to 400 °C heat source at the hot side but the temperature of the cold side of the module cannot go above 200 °C. This difference is due to the bonding process which uses materials with different melting point for each side of the module.

3.1. Thermal and mechanical part

The thermal and mechanical part is presented in Fig. 4.

An aluminum heat sink with fins is mounted on the hot side of the TE modules. An aluminum tank (2 L) filled with water is used as a cold side exchanger. This water which is the cold heat sink for the TE generator will be the domestic hot water in a real application. A compressive load is applied in the centre of the tank to reduce thermal contact resistance.

For the experiment, it was easier to make measurements with the load applied in the centre but in the final design, it will be applied along the edges of the tank. Thermal grease is used for each

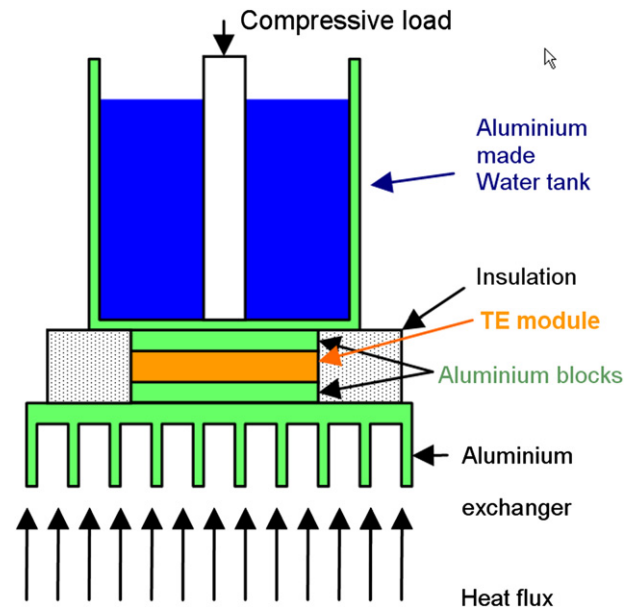


Fig. 4. Schematic of the thermal and mechanical parts of the TE generator.

contact. To reduce thermal contact resistance, the aluminum surface is polished with a milling machine to get a proper flatness around 25 μm (standard deviation of height). A pressure up to 7.5 bar can be applied to the TE module. The pressure is measured with a strain gauge sensor for compression measurements (Sensel SM1182). Thermal insulation is used between the two exchangers (see Fig. 4). Two aluminum blocks instrumented with thermocouples are added on each side of the TE module as shown in Fig. 5. Other thermocouples allow us to measure the water and the hot air temperatures.

The operating parameters of the improved stove are reproduced with a gas heater. The temperature and the flow rate of the hot air are the same as the values obtained with the stove. The use of the gas heater allows us to simplify the experimental procedure of the TE generator study.

3.2. Electrical part

Two points are particularly important: the storage of electrical energy and the voltage regulation.

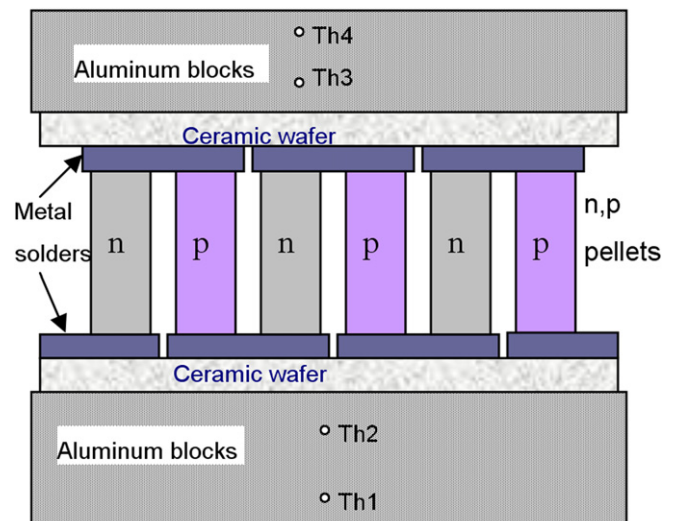


Fig. 5. Schematic of a thermoelectric module.

Table 1
TE generators using bismuth telluride commercial modules.

Authors	Heat sink (cold side)	Power per module
Nuwayhid et al., 2003 [11]	Natural air cooling	1 W
Nuwayhid et al., 2005 [12]	Natural air cooling	4.2 W
Nuwayhid and Hamade, 2005 [13]	Heat pipes cooling	3.4 W
Lertsatitthanakorn, 2007 [14]	Natural air cooling	2.4 W
Mastbergen and Wilson, 2007 [7]	Forced air cooling (1 W)	4 W regulated
"BioLite" 2009 [16]	Forced air cooling (1 W)	1–2 W
Champier et al. "TEGBioS" 2009 [17]	Water cooling	5 W
Rinalde et al., 2010 [9]	Forced water cooling	10 W ^a

^a Part of this power should be used to power the pump.

At the beginning of the burning, the temperatures are very low and the TE generator does not produce any electricity. The autonomy of the cooking stove requires a battery to store the electrical energy produced by the TE modules and to restore it at the beginning of the burning.

A lead-acid battery has been chosen because it currently offered the best response in terms of price, energetic efficiency, lifetime and availability in developing countries.

VRLA (valve regulated lead-acid) batteries have been selected as they can be used directly in home environment; they are self-contained and safe, they can be stored and used in any orientation and are maintenance free. In normal use, they are environmentally friendly.

Since the fan, LEDs, radios and cell phones only need low voltage and also because of availability, we have chosen '6V' batteries.

The expected service life of the standard VRLA battery is typically 5 years when used in floating voltage. For a 6 V battery the floating voltage is about 6.75 V.

The lead-acid charging process is somewhat lenient as long as it is not overcharged, overheated, or let to form excessive gas. There are different methods of charging lead-acid battery [19,20]. We have chosen a simple but efficient method: constant voltage, current limited charging. In the initial charging stage, the current flowing into the battery is limited to a value of the maximum charging current about 20% of capacity in Ah. In the second stage the constant voltage maintains the battery in a fully charged float condition.

An electrical power of about 6 W available for the battery implies a charging current of 0.9 A. As the maximum charging current is about 1/5 of the capacity, a 4.5 Ah battery is selected for our experiment.

Since the heat produced by the combustion vary a lot during the use of the stove (wood supply, quality of wood, cooking) and the temperature of the water is modified when people take or add water, the temperatures on each side of the TE generator vary a lot. As a consequence, the output voltage of the generator fluctuates a lot. A power electronic circuit is required to regulate the output voltage and to boost it to the battery level. As the voltage of the one module TE generator is low a boost regulator is necessary.

An electronic converter (Fig. 6) has been developed using a step-up switching regulator MAX642 which works in the 5 mW to 10 W range with a very good efficiency. Some electronic circuits are added to limit the charging current of the battery.

This electronic converter was tested with a laboratory power supply. Simple tests made on a resistive load showed that the efficiency stands in a range from 80% to 85% [17,18].

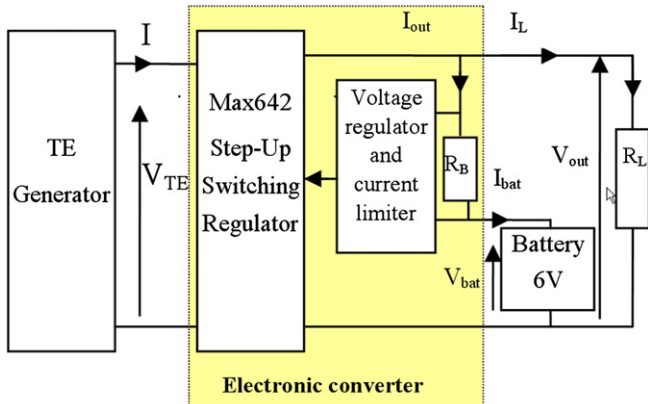


Fig. 6. Schematic of an electronic part of the TE generator with the measurement.

3.3. One-dimensional steady-state analysis

TE modules are made of n couples of p -type and n -type semiconductor pellets connected with metal solder. For electrical insulation, two ceramic wafers sandwich the pellets (Fig. 5).

We used the one dimensional model commonly described in literature (1-D heat flow) of a typical TE module made of n thermocouples [21,22].

These equations are obtained from the study of a single n - or p -type element assuming that all connections between the pellets are perfect: no electrical and thermal resistance.

We also assume that there is no conduction, convection or radiation via the ambient, which means that the only path to transfer heat from one side of the pellet to the other is through the TE material. These assumptions give the following TE equations for the heat released on the cold side, q_c , the heat absorbed on the hot side, q_h , and for the generated electrical power P_{elec} .

$$q_h = n \cdot \left[\alpha_{pn} \cdot I \cdot T_h - \frac{R_{pn} \cdot I^2}{2} - K_{pn} \cdot (T_c - T_h) \right], \quad (1)$$

$$q_c = n \cdot \left[\alpha_{pn} \cdot I \cdot T_c + \frac{R_{pn} \cdot I^2}{2} - K_{pn} \cdot (T_c - T_h) \right], \quad (2)$$

$$P_{elec} = n \cdot \left[\alpha_{pn} \cdot I \cdot (T_h - T_c) - R_{pn} \cdot I^2 \right], \quad (3)$$

where I is the current, T_c and T_h are respectively the temperatures of the cold side and the hot side of the TE module.

The parallel thermal conductance, K_{pn} , serial electrical resistance, R_{pn} , and Seebeck coefficient, α_{pn} of one thermocouple are:

$$K_{pn} = \frac{\lambda_n \times S_n}{L_n} + \frac{\lambda_p \times S_p}{L_p}, \quad (4)$$

$$R_{pn} = \frac{\rho_n \times L_n}{S_n} + \frac{\rho_p \times L_p}{S_p}, \quad (5)$$

$$\alpha_{pn} = \alpha_p - \alpha_n, \quad (6)$$

L_n , L_p and S_n , S_p are respectively the leg length and cross-sectional area of the pellets.

α_p , α_n , λ_n , λ_p , ρ_n , and ρ_p are temperature dependent and are evaluated at the average temperature $T_a = (T_h + T_c)/2$, the values are taken from the Thermoelectric Handbook - Material Properties n - and p -type Bi_2Te_3 [21,23].

For the selected commercial modules $n = 126$, $L_p = L_n = 1.4$ mm, $S_n = S_p = 6.6$ mm².

For an electric load R_E , current I can be calculated with

$$I = \frac{E_o}{nR_{pn} + R_E} = \frac{n \cdot \alpha_{pn} \cdot (T_h - T_c)}{nR_{pn} + R_E}, \quad (7)$$

E_o is the open circuit voltage of the TE module.

The maximum output power P_{elec}^{max} will be obtained for a matched load which means $nR_{pn} = R_E$.

The temperature T_c and T_h can be evaluated by using a thermal resistance model (Fig. 7).

R_{ce1} , R_{ce2} are the thermal resistances of the ceramic wafers, R_{cc} and R_{ch} are the contact thermal resistances between wafers and aluminum blocks. The temperature measurements (T_{h1} , T_{h2} , T_{h3} and T_{h4}) are taken with type K thermocouples placed in holes in each of the two aluminum blocks (Figs. 5 and 8). The temperatures of the hot and cold sides of ceramic wafers of the module T_{sh} , T_{sc} and the

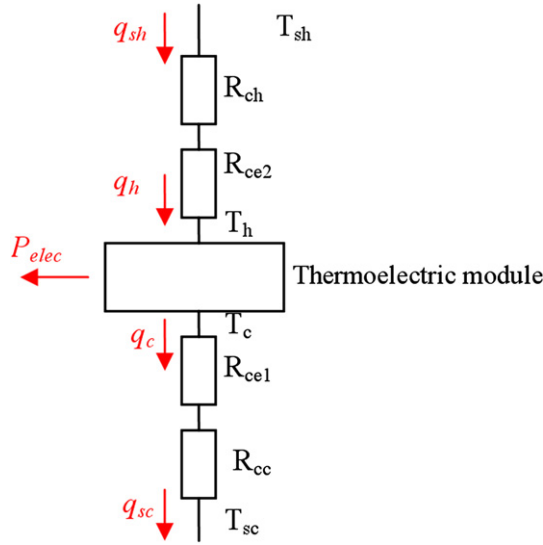


Fig. 7. Thermal resistance model of the thermoelectric module.

temperatures T_h and T_c are calculated by using the energy conservation assuming that the aluminum blocks are well insulated from the ambient: $q_c = q_{sc}$ and $q_h = q_{hc}$. For example

$$q_c = \frac{T_{h4} - T_{h3}}{R_{ala}} = \frac{T_{h3} - T_c}{R_{alb} + R} \quad (8)$$

with

$$R_{ala} = \frac{e_a}{\lambda_{al} \cdot S}, R_{alb} = \frac{e_b}{\lambda_{al} \cdot S} \quad (9)$$

$$R = \frac{e_c}{\lambda_{ceram} \cdot S} + \frac{1}{h_{contact} \cdot S} + \frac{e_s}{\lambda_{solder} \cdot S} \quad (10)$$

λ_{al} , λ_{ceram} , and λ_{solder} are the thermal conductivities of respectively the aluminum, the ceramic wafers and the metal solders. $h_{contact}$ is the contact heat transfer coefficient or thermal contact coefficient.

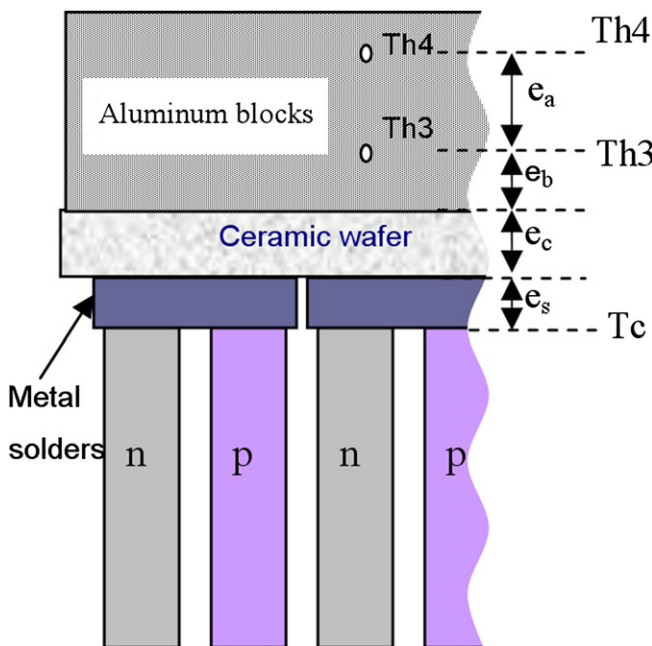


Fig. 8. Details of a thermoelectric module.

The thermal contact resistance $1/h_{contact}S$ is introduced to take into account that the contact between ceramic and metal is not perfect.

According to equation (8):

$$T_c = T_{h3} + \frac{(R_{alb} + R)}{R_{ala}} (T_{h3} - T) \quad (11)$$

$$T_c = T_{h3} + \frac{e_b + e_c \frac{\lambda_{al}}{\lambda_{ceram}} + e_s \frac{\lambda_{al}}{\lambda_{solder}} + x}{e_a} (T_{h3} - T_{h4}) \quad (12)$$

with

$$x = \frac{\lambda_{al}}{h_{contact}}$$

the analysis was done with $e_a = 13.9$ mm, $e_b = 3.2$ mm, $e_c = 1$ mm, $e_s = 0.7$ mm, $\lambda_{solder} \approx \lambda_{al} = 237$ W m⁻¹ K⁻¹, $\lambda_{ceram} = 25$ W m⁻¹ K⁻¹. The parameter x ($h_{contact}$) will be fitted by comparison between the measured power and the calculated power.

4. Results

The temperatures, tensions, currents and pressure (Pr) applied on the module are recorded by an Agilent 34970A Data Logger. The measurement system enables us to obtain a precision of 0.01% for the tensions, 0.1% for the currents and 0.5 °C for the temperatures. But, because of the difficulty in measuring a temperature accurately, the temperature errors are evaluated to 1 °C. The precision of the pressure measurements is 0.25%.

T_{h1} , T_{h2} , T_{h3} , T_{h4} , Pr and also V_{out} , V_{bat} , I_{bat} and I_L (see Fig. 6) are recorded.

The output power from the TE module $P_{elec} = V_{TE} \cdot I$ and the available power for the end users are calculated:

$$P_{av} = V_{out} \cdot I_L + V_{bat} \cdot I_{bat} \quad (13)$$

4.1. Influence of the contact resistances

The objective of this first experiment was to evaluate the influence of the pressure on the contact resistances.

For this experiment, the electronic DC–DC regulator was replaced by a simple resistor. Its value was around 1.2 Ω in order to be almost adapted to the value of internal load of the TE module. Temperature T_c was kept nearly constant by adding ice during the experiment, so that the temperature difference (ΔT) was almost constant (120 ± 5 °C). Keeping T_c and T_h constant guarantees that there is no variation of the internal physical properties (K_{pn} , R_{pn} , α_{pn}) of the TE modules.

The slight variations of the temperature difference were corrected by using the relation (14) given by Min and Rowe [24].

$$P_{elec}(120^\circ\text{C}) = P_{elec}(\Delta T) \cdot \left(\frac{120}{\Delta T} \right)^2 \quad (14)$$

The compressive load is increased from 0 to 750 kPa and then decreased again to 0 (Fig. 9). A one shot measurement was taken 24 h later.

Fig. 9 shows that the electrical output power increases with the pressure from 0 to 400 kPa. Beyond there is only a slight increase in the output power over the tested loading range (the differences in all values are less than 5% and probably not significant).

When the mechanical load decreased, the output power remained constant. This is interesting as it shows that thermal expansion will not probably affect the electrical output power during a normal operation. The last measurement made 24 h later shows that the prototype does not keep this property after cooling.

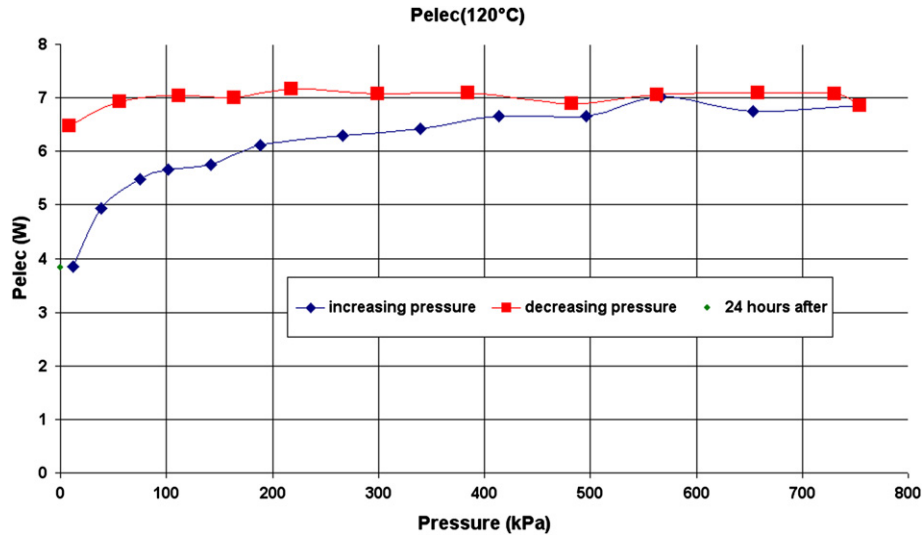


Fig. 9. Measured electrical power (P_{elec}) as a function of the pressure for a temperature difference of 120 °C.

This first experiment shows that a choice of 500 kPa (5 bar) is a reasonable value to minimize the contact resistance. A more important value might be destructive for the delicate thick ceramic plate because of the thermal expansion during the transient states.

4.2. Electrical power measurements

This experiment aimed at determining the electrical power (regulated and not regulated) of the TE generator, comparing it with the theoretical power given by the 1D model and assessing the value of the thermal contact resistance. The final goal of the measurements was to find out if we got the maximum available power from our prototype and to analyze what could be improved.

For this experiment, the complete TE generator including the electronic part with a load resistor of 12 Ω was tested. Fig. 10 shows the hot and cold side temperatures and the corresponding electrical power for a half hour experiment.

The TE module produced a maximum electrical power of 9.5 W and because of losses in the electronic convertor a maximum power of 7.6 W was available.

The resistor R_E seen by the TE module can be calculated by using the voltage and current measurements: $R_E = V_{TE}/I$.

This impedance R_E is not exactly matched but it is possible to calculate the maximum power that would be obtained if the electronic convertor matched the load.

As $V_{TE} = E_o R_E / (R_E + nR_{pn})$, then P_{elec} can be expressed as:

$$P_{elec} = \left(\frac{E_o \cdot R_E}{R_E + nR_{pn}} \right)^2 \cdot \frac{1}{R_E} \quad (15)$$

and for a matched load

$$P_{elec}^{max} = \frac{E_o^2}{4nR_{pn}} \quad (16)$$

The maximum power (dashed line) on Fig. 11, can be calculated by:

$$P_{elec}^{max} = P_{elec} \frac{(R_E + nR_{pn})^2}{4 \cdot nR_{pn} \cdot R_E} \quad (17)$$

Then this maximum power is compared with the power obtained with the 1D model for a matched load using x as fitting parameter. A value of $h_{contact}$ of 20,000 W m⁻² K⁻¹ guarantees a good matching of the two curves for different trials (variations on

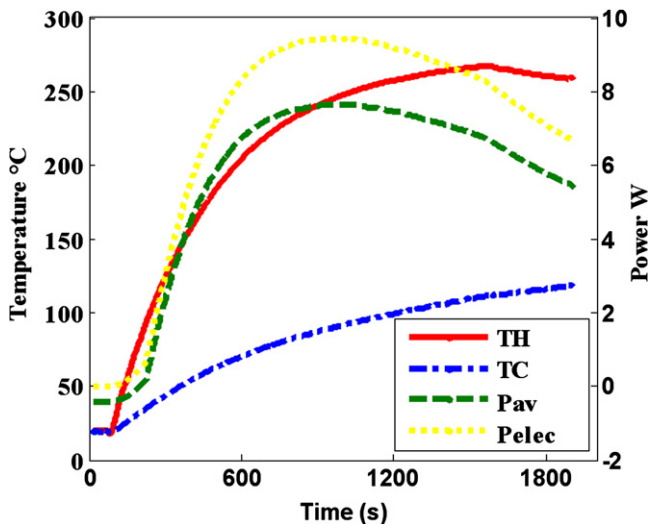


Fig. 10. Cold and hot side temperatures and electrical powers during the experiment.

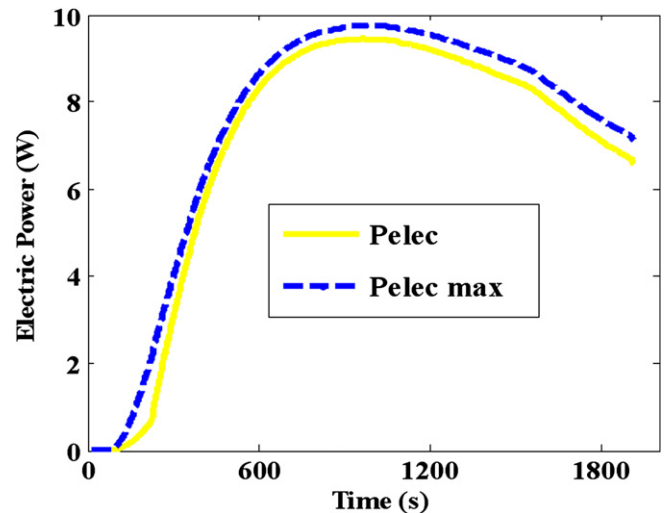


Fig. 11. Measured electrical power and calculated maximum output electrical power.

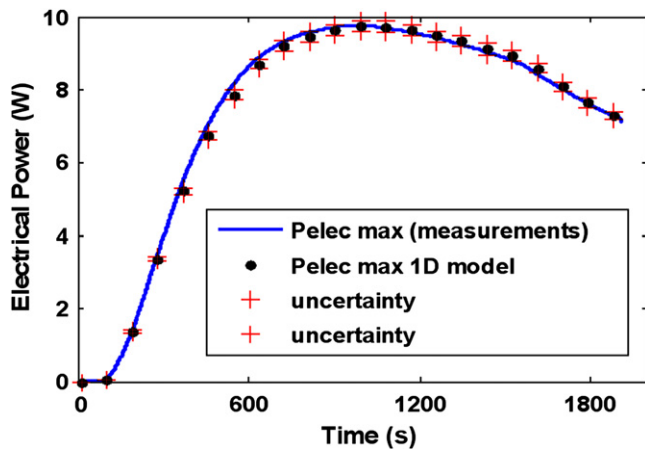


Fig. 12. Comparison between measurements and 1D model of the TE generator.

the input heat flux). This value of about $20,000 \text{ W m}^{-2} \text{ K}^{-1}$ corresponds to a good contact according to the reference [25].

The results are presented in Fig. 12. Uncertainties are evaluated for a 0.5 mm error on the measurements of e_a and e_b . The value found for h_{contact} shows that in this prototype we have almost reached the maximum power available from such a TE generator. The mechanical and thermal design is optimized.

The point to be improved is the matching between the TE module and the electronic convertor.

In our experiment the load was chosen to be near the matched load as seen in Fig. 11 but in different uses the mismatch could be very important and the output power could be much lower than $P_{\text{elec}}^{\text{max}}$.

As the output current changes, the working point moves and it will be necessary to use a MPPT (maximum power point tracking) electronic regulator [26]. This can be done by a cheap microcontroller in the electronic circuit. Nowadays microcontrollers have very low power consumption and will not penalize the regulator in comparison with the benefits given by the matching load tracking. A microcontroller could also add some intelligence to control the fan and thus to slow down the gas speed in case of an increasing temperature exceeding the maximum temperature tolerated by the hot side of the TE module.

4.3. Economic perspective

The economic study is important to fill a gap between the laboratory prototype and the dissemination of the multifunction cooking stove equipped with TE generator. The other challenger producing electricity in these countries without large power plant is photovoltaic. An economic analysis is presented in Table 2. The cost was calculated for different volumes of production according to the price of the individual components. By comparison the average price of 10 W (supplied with their regulator) solar panels in

France is about 13 € per watt. Even if the cost estimated in Table 2 does not include the labor cost, the result show that the cost per watt of TE module is very competitive with solar panels.

5. Conclusion

An experimental TE generator suitable for electricity production in multifunction biomass stoves has been presented. The complete system from the heat source up to the end users electricity production, including electronic convertor and battery charging, has been studied.

The influence of thermal contact has been shown. A compressive load of about 5 bar is necessary to minimize the thermal contact and get back to a sufficient output power.

The comparison between the experimental data and the commonly used one dimensional TE model shows a good agreement. The very reasonable value of the contact resistance validated by the comparison shows that the mechanical design of the generator is well optimized. In the case of an almost matched load, the TE module has produced up to 9.5 W. Due to the fluctuating output, an electronic boost regulator stores this electrical energy in a battery with an around 6.7 V stabilized voltage. The maximum power of stabilized electricity available for the end users is around 7.6 W obtained with an economic cost competitive with solar panels.

Further work is planned to prevent the decrease in output power in case of a mismatched load by adding a maximum power point tracking convertor. It will be obtained at a lower cost by adding an ordinary microcontroller. This microcontroller could also prevent the TE generator from overheating by monitoring the temperature on the hot side and controlling the speed of the fan to eventually decrease combustion.

Another experimental device will be carried out in order to incorporate the TE generator in a real improved stove. This prototype will enable us to validate the complete system before field testing in developing countries.

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Table 2
Projected cost of the TE generator.

Components	Single unit cost	100 samples	High volume cost 10,000 samples
Electronic part	31€	15€	13€
Thermal part (aluminum exchangers)	31 €	22€	12€
TE module	67€	35€	15€
8 W TE generator	129€	72€	40€
	16€ per watt	9€ per watt	5€ per watt

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